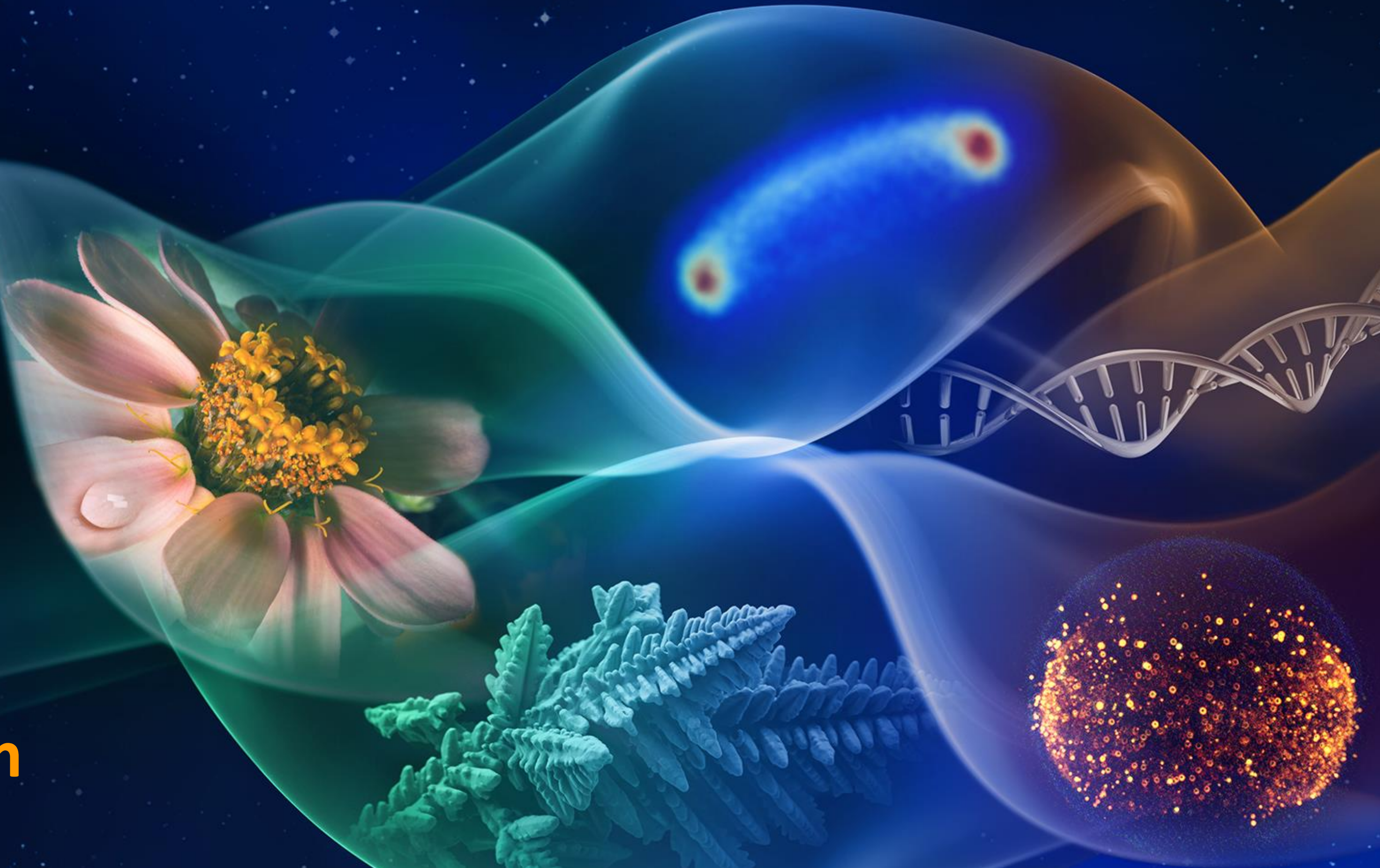
National Aeronautics and Space Administration

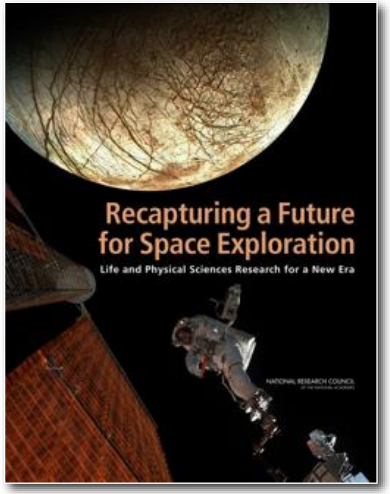


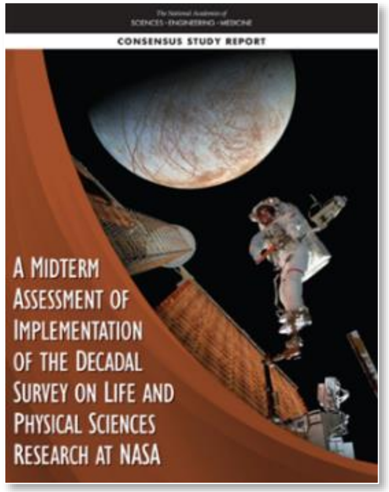
BPAC: Fundamental Physics Program

Mike Robinson 11/16/2022
Fundamental Physics Program Scientist
NASA Science Mission Directorate
Biological and Physical Sciences Division

2023-2032 Decadal Survey for Biological and Physical Sciences Research in Space

- **A National Academies of Sciences, Engineering, and Medicine report**
  - Purpose is to generate consensus recommendations for a comprehensive vision and strategy for a decade of transformative science
  - Focused, select number of highest priority recommendations
  - Expected to be delivered in the summer of 2023
- **NASA's Decadal response plan**
  - Share initial plan at a Town Hall ~90 days post receipt
  - Formulate a phased approach to implementation
    - Identify initial activities starting in FY24
    - Propose Decadal response budget beginning FY25
    - Staggered start of flight programs
- **Current activities while awaiting new Decadal**
  - Identifying commercial space capabilities and science community needs to accelerate the pace of research in space
  - New solicitations in focus areas (Quantum Science, Thriving in Deep Space (TIDES))





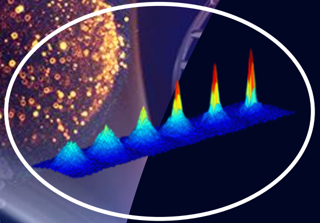
BPS Fundamental Physics Interests

- **Transformational experiments that require the unique environment of space**
  - Microgravity
- **Quantum mechanics and general relativity**
- **Searches for dark matter and dark energy**
- **Tests of general relativity and the equivalence principle**
- **Exotic physics**
- **Atomic clocks**
- **Atom interferometry**
- **Quantum entanglement**
- **Collaboration**
- **Etc…**

Making Quantum Leaps in Quantum Science by

Seeking answers to today's most intriguing questions

Exploring the Quantum Realm

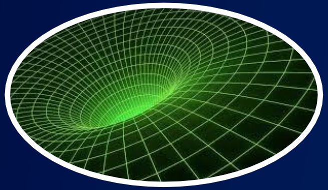


- **What are the Quantum Properties of atoms and molecules?**

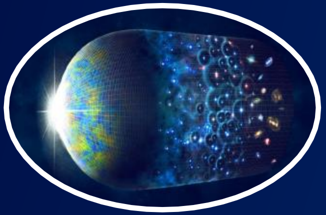
- **How is Quantum Entanglement influenced by gravity?**

- **How does complexity & order arise from Quantum interactions?**

New Physics with Quantum Tools



- **Is Einstein's General Relativity valid under all experimental conditions?**



- **What is the true nature of Dark Energy?**

- **Is Dark Matter an ultra-light field?**

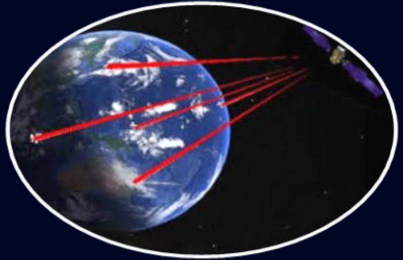
In pursuit of these questions, we will

- **Transform our understanding of matter, space, and time**
- **Develop new technologies that enable Space & Earth commercial opportunities**
- **Inspire students to continue the pursuit of new NASA discoveries**

Quantum Science Decadal Keystone Mission Candidates

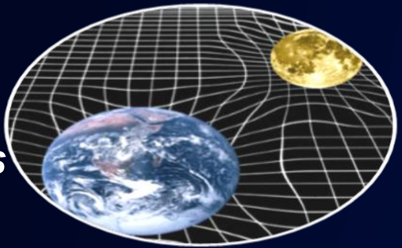
Research on Free Flyer

Gravitation and Dark Matter



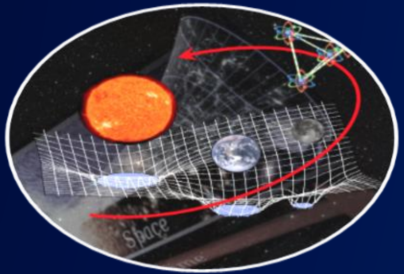
Fund Physics with Optical Clock Orbiting in Space (FOCOS)

Quantum/ Gravitation Correlations



Space Experiments Exploring Quantum Entanglement and Relativity(SEEQER)

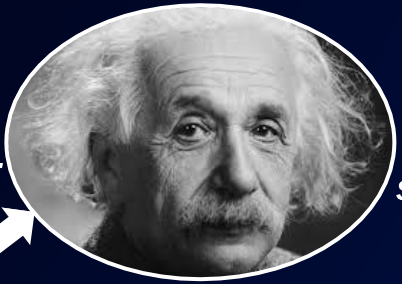
Gravitation and Dark Energy



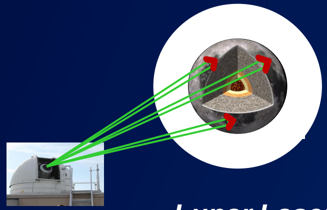
Gravity Observation and Dark Energy Detection Explorer in the Solar System (GODDESS)

Research on ISS, Gateway (DSG), etc.

Gravitation with Quantum Matter

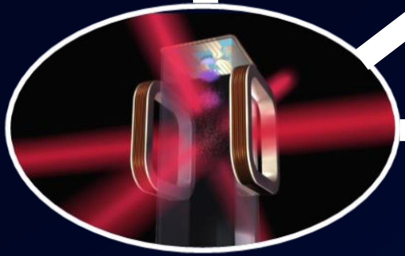


Quantum Test of Equivalence and Space Time (QTEST)



Lunar Laser Ranging

Quantum Matter



CAL SM4

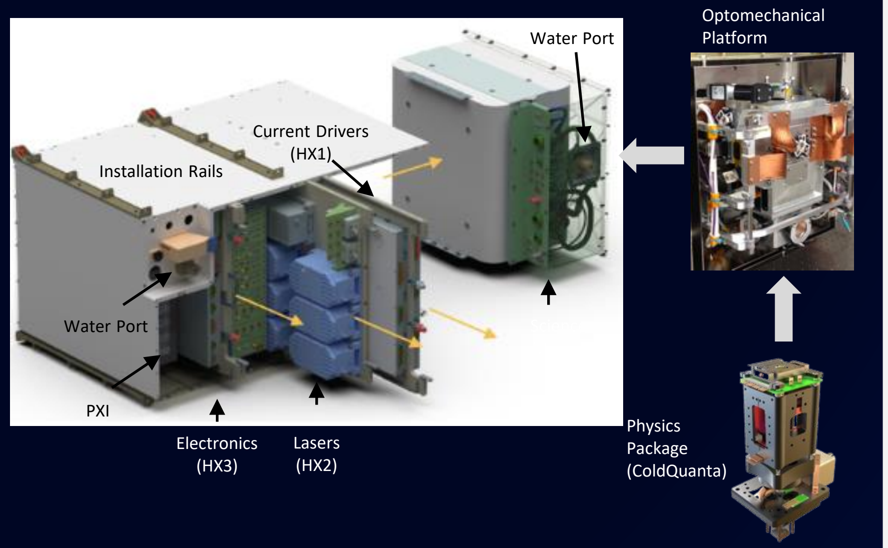
BECCAL (DLR)

Quantum Explorer (QUEX)

Cold Atom Lab (CAL)

- Dual species Rb/K BEC and atom interferometry on ISS
- User facility operated by JPL

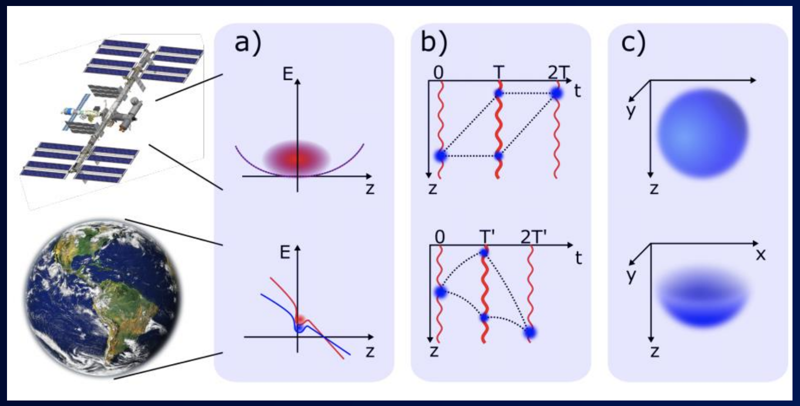
CAL as a Quantum Technology Pathfinder



Matures critical hardware for spaceborne QT

- Atomically referenced/stabilized laser systems
- Optomechanics and fiber-based laser subsystems
- Ultra-high vacuum Physics Packages
- Low-noise electronics and control system
- Highly stability, low SWaP, transportable quantum facility in a box
- Atom Interferometry

Space-based experiments



a) Absence of gravitational sag allows for extreme cooling protocols and overlap of multiple co-trapped atomic species.

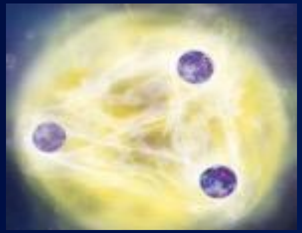
b) Long free-fall durations in space allow high-precision measurements within relatively small apparatus sizes.

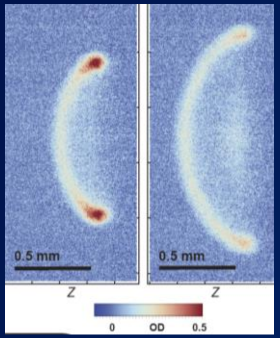
c) Microgravity enables novel trapping geometries (e.g. shell potentials for BECs) at ultra-low energy scales.

Additionally, space offers access to orbits with variable gravity, earth and planetary sciences, and environments inaccessible to quantum sensors in terrestrial labs.

CAL Flight Investigations

- Zero-G Studies of Few and Many Body Physics (**PI E. Cornell, University of Colorado, Boulder**)
    - Xie, et al., “Observation of Efimov Universality across a nonuniversal Feshbach resonance in K-39.” PRL, Dec 2020
- Atom interferometry Will Pave the Way for Definitive Space-based Tests of Einstein’s Theory of General Relativity (**PI N. Bigelow, University of Rochester, Co-PI W. Ketterle, MIT, Co-PI W. Phillips, NIST**)
    - Gaaloul, et al., “A space-based quantum gas laboratory at picokelvin energy scales.” Accepted, Nature Communications
- Microgravity dynamics of bubble-geometry Bose-Einstein condensates (**PI Nathan Lundblad, Bates College**)
    - Carollo, et al., "Observation of ultracold atomic bubbles in orbital microgravity.“ Nature, 18 May 2022





CAL Flight Investigations

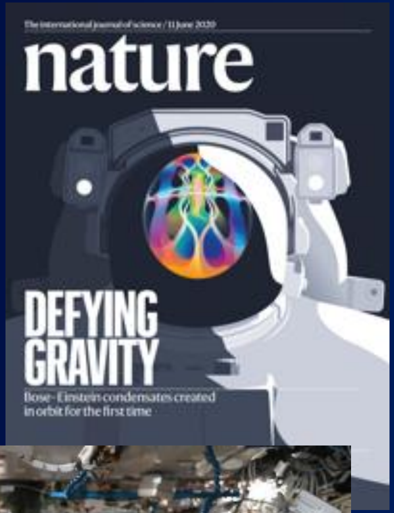
- Fundamental Interactions of Atom Interferometry with Ultracold Quantum Gases in a Microgravity Environment (**PI Jason Williams, JPL**)
  - Aveline, et al., "Observation of Bose–Einstein condensates in an Earth-orbiting research lab.“ Nature, Jun 2020, Cover article

- Development of Atom Interferometry Experiments for the International Space Station’s Cold Atom Laboratory (**PI Cass Sackett, University of Virginia**)
  - Pollard, et al., "Quasi-adiabatic external state preparation of ultracold atoms in microgravity.“ Microgravity Science & Technology, Dec 2020

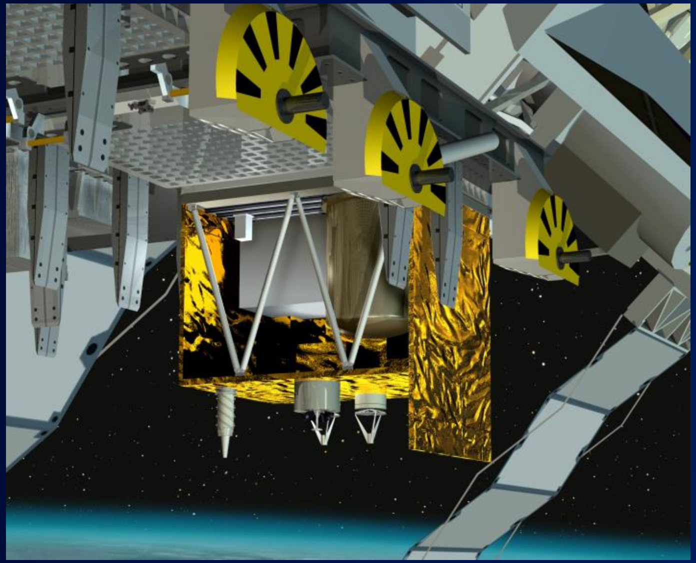
- *Quantum Science & Technology* – Special issue dedicated to cold atoms in space – expected late 2022
  - Guest edited by Rob Thompson (JPL) and Cass Sackett (UVA)
- First observation of dual species atom interferometry in space, Rb/K
  - Publication in preparation for Nature

Current projects

- **Cold Atom Lab (CAL)**
  - Dual species Rb/K BEC and atom interferometry on ISS
  - User facility operated by JPL
- **BECCAL**
  - DLR collaboration follow on to CAL, 2026
  - Upgraded capabilities
  - Blue detuned box potentials and optical dipole trap
  - Equivalence principle tests
  - Dark energy search
  - Many-body physics



Current projects

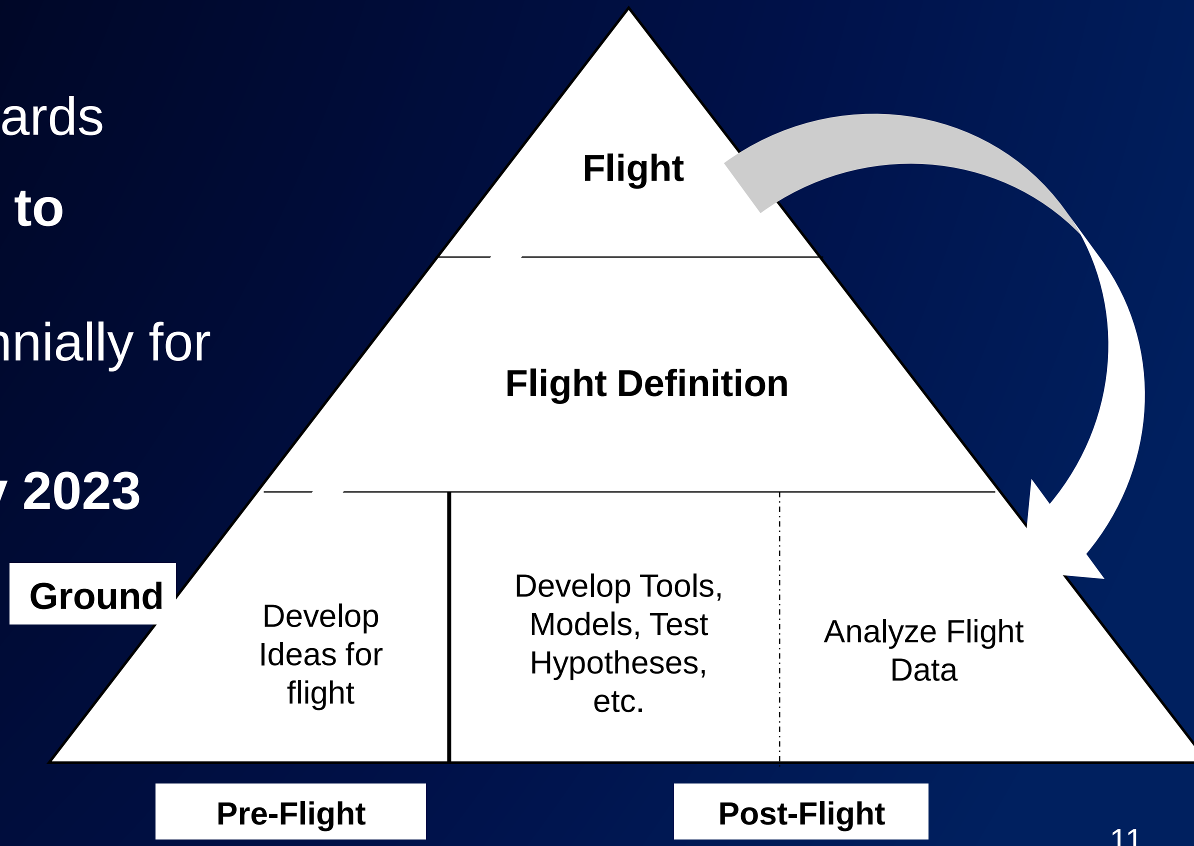


Artist rendering of ACES on ISS. Source: ESA

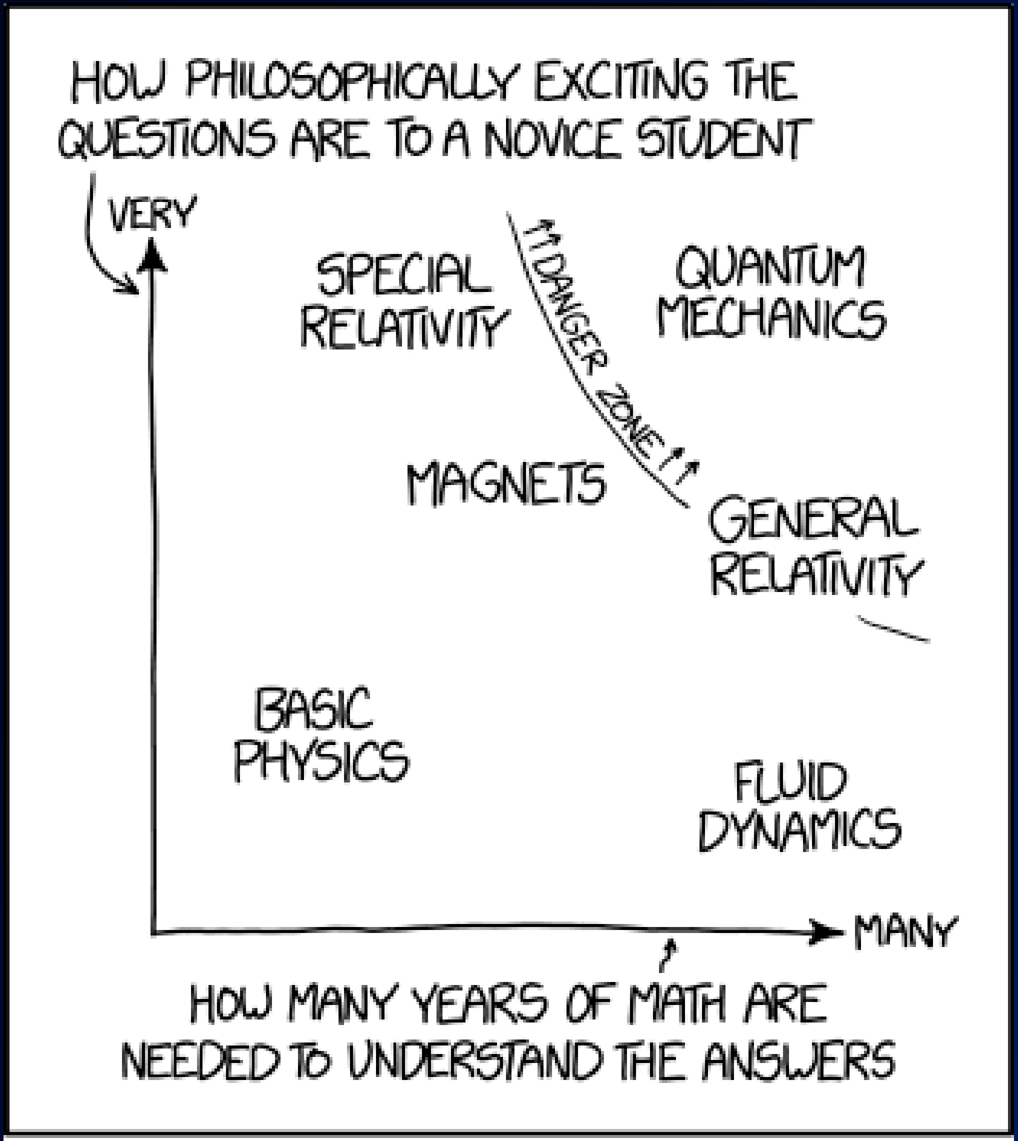
- **Atomic Clock Ensemble in Space (ACES)**
  - ESA collaboration, 2025
  - 10^{-16} Cs atomic clock on ISS
  - Gravitational redshifts
  - Physical constants
- **Direct Detection of Dark Energy in the Einstein Elevator (D3E3)**
  - DLR collaboration
  - Atom interferometry in the Einstein elevator
- **Space Entanglement and Annealing Quantum Experiment (SEAQUE)**
  - Demonstrate source of entangled photons
  - Validate laser annealing in single-photon-detectors
  - Deep Space Quantum Link test bed
    - Long baseline Bell tests
    - Equivalence principle

Future Portfolio

- **Heavily influenced by upcoming Decadal Survey**
  - Many quantum ideas submitted to committee
- **2022 fundamental physics NASA Research Announcement (NRA)**
  - Proposals under review
  - Notionally ~7 ground and ~3 flight awards
- **Expectation to restore annual cadence to fundamental physics NRAs**
  - Annual for ground investigations, biennially for flight
- **Fundamental Physics Workshop – May 2023**
- **Fundamental Physics Analysis Group**



Questions?

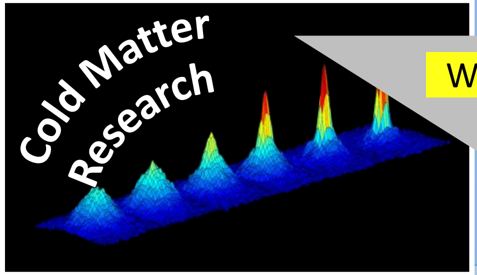


WHY SO MANY PEOPLE HAVE WEIRD IDEAS ABOUT QUANTUM MECHANICS

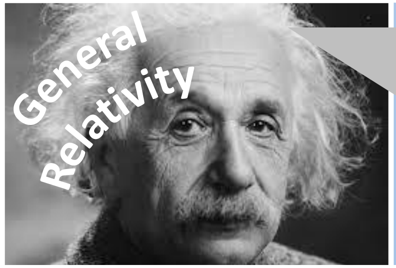
[xkcd: Quantum]()

Quantum Science Roadmap

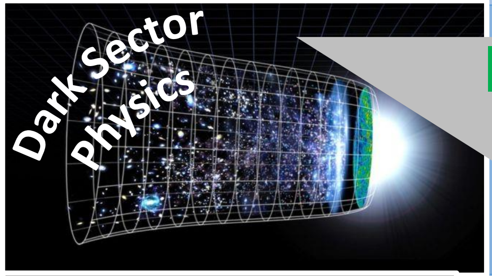
Present	Near Term	Formative	Visionary



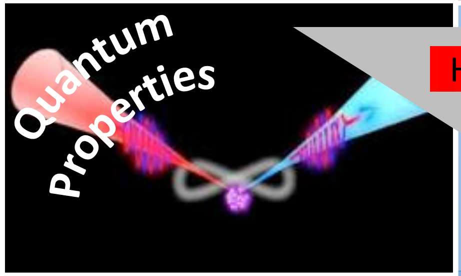
- What are the properties of quantum systems of atoms and molecules?
- How can we design useful science systems and sensors using quantum properties?
- How does complexity & order arise from Quantum interactions?



- Is Einstein's theory of General Relativity valid under all experimental conditions?
- Under what conditions will Einstein's Weak Equivalence Principle be violated?
- How can General Relativity be unified with Quantum Mechanics?



- Is the Chameleon or Symmetron fields Dark Energy?
- Are ultra-light scalar fields responsible for Dark Matter?
- Are scalar fields responsible for Dark Energy?



- How does complexity & order arise from Quantum interactions?
- What is the role of free will in quantum mechanics?
- Is there quantum interference from curved spacetime?
- Is Quantum Mechanics locally real?

Missions

	Partners	Mission	Research
Present	DLR	CAL-SM3	CMR/QP
Present	DLR	D3E3	DSP
Near Term	DLR NSF	CAL-SM4	CMR/QP
Near Term	ESA NIST CNES DLR	ACES	GR
Formative	DLR NSF	BECCAL	CMR/QP
Formative	DLR	QTEST4	GR/DS
Formative	DLR SCAN	SEEQER	QP/GR
Visionary	DLR NSF	Quantum Explorer	CMR/QP
Visionary	NIST DLR	FOCOS	GR/DS
Visionary	TBD	GODDESS	DS/GR

Free Flyer Keystone Mission Candidate - SEEQER

Space Experiments Exploring Quantum Entanglement and Relativity

Objectives

Understand quantum system behavior and test the influence of gravity and relativistic effects on quantum mechanics using photon entanglement separated by light-second distances

- Long baseline Bell tests with entangled photons exposed to different reference frames
- Test theories of gravitationally induced decoherence
- Test the strong form of Einstein's Equivalence Principle
- Probe the influence on human decision making on quantum systems

Experimental Approach & Heritage

- Mission configurations under study for Lunar Gateway to ISS/Earth baseline.
- Work closely with partners to validate and refine SEEQER architecture through participation in planned SCAN, CSA, Singapore, DLR, and ESA experiments in Low Earth Orbit.
- Leverage heritage from deep space optical communications

Relevance/Impact

- 2011 Decadal FP2: Understand the fundamental forces and symmetries of nature
- 2017 FPSRB White Paper
- A violation of Einstein's theories or of quantum mechanics at any level will require rewriting physics textbooks.
- Contribute to establishing a grand unified theory of physics that includes gravitation.
- Pioneer development of infrastructure for a space quantum network.

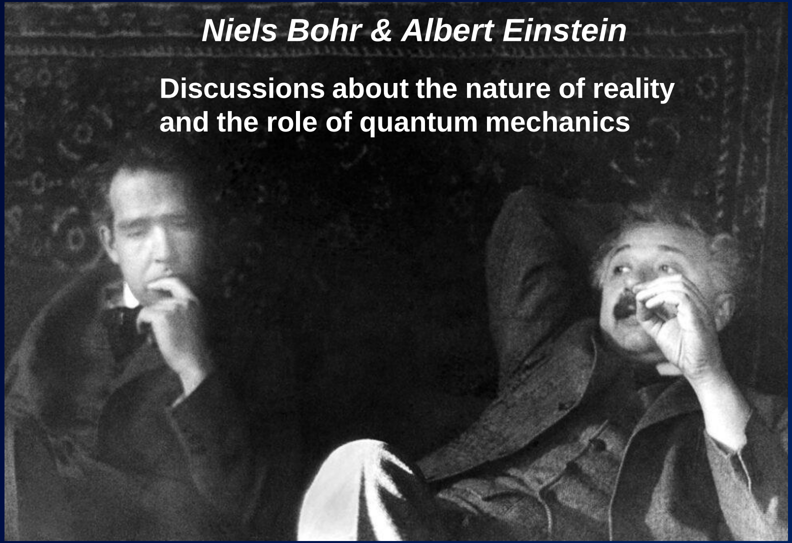
Project Development Approach

- Use science definition team to finalize science objectives, science envelope requirements, mission concept, and technology tall poles.
- Perform technology maturation of critical elements, including entangled photon source, detector, and timing architecture
- Select investigators through ROSES NRA.

Artist Rendition of SEEQER

Niels Bohr & Albert Einstein

Discussions about the nature of reality and the role of quantum mechanics



Free Flyer Keystone Mission Candidate - GODDESS

Gravity Observer for Detection of Dark Energy in Solar System

Objective

- Use atom interferometry to seek direct evidence of a class of proposed scalar-field dark energy candidate particles screened near regular matter
  - Chameleon, Symmetron, Galileon
- Search for ultra-light (<< 1 eV) dark matter candidates
- Search for deviations from General Relativity
- Provide more stringent limits of Cosmological Constant
- Detect Gravitational waves, including their direction in frequency band between LIGO and LISA

Experimental Approach & Heritage

- Search for Chameleon and Symmetron in University of Hannover Einstein Elevator drop tube.
- Use a tetrahedral space mission configuration of atomic drag-free sensors ~ 1 au from the Sun.
- Link sensors using laser ranging.
- NIAC Phase 1 study completed. Phase II study on-going.

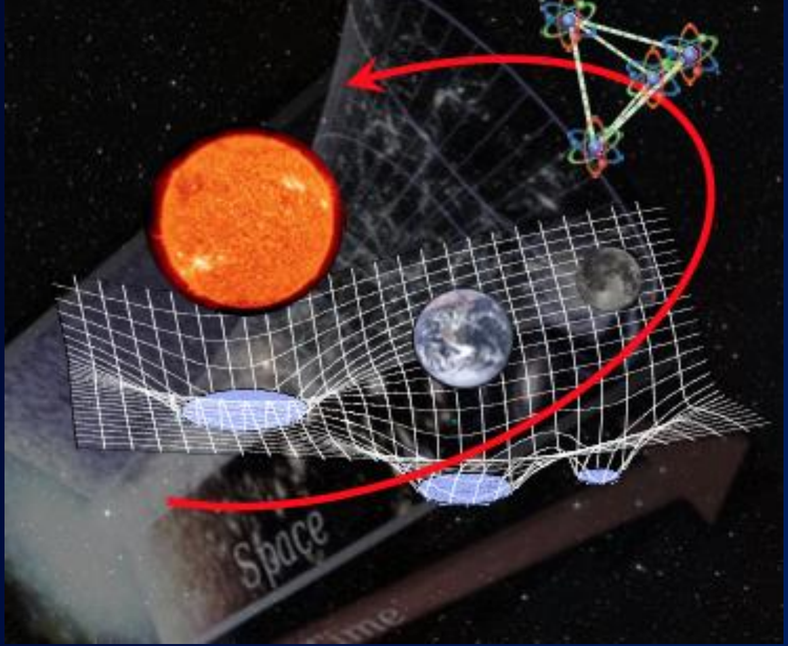
Relevance/Impact

- 2011 Decadal FP2: Understand the fundamental forces and symmetries of nature
- 2003 Q2C NRC Report & 2017 FPSRB White Paper
- Discovering what the nature of dark energy is would be ground-breaking as would finding deviations to General Relativity and identifying the dark matter particle.
- Enormous discovery potential with mid-band directional GW detection.

Project Development Approach

- Complete Einstein Elevator developmental project in 2026.
- Use NIAC phase II activity to mature concept.
- Select investigators through ROSES NRA

Artist Rendition of Goddess



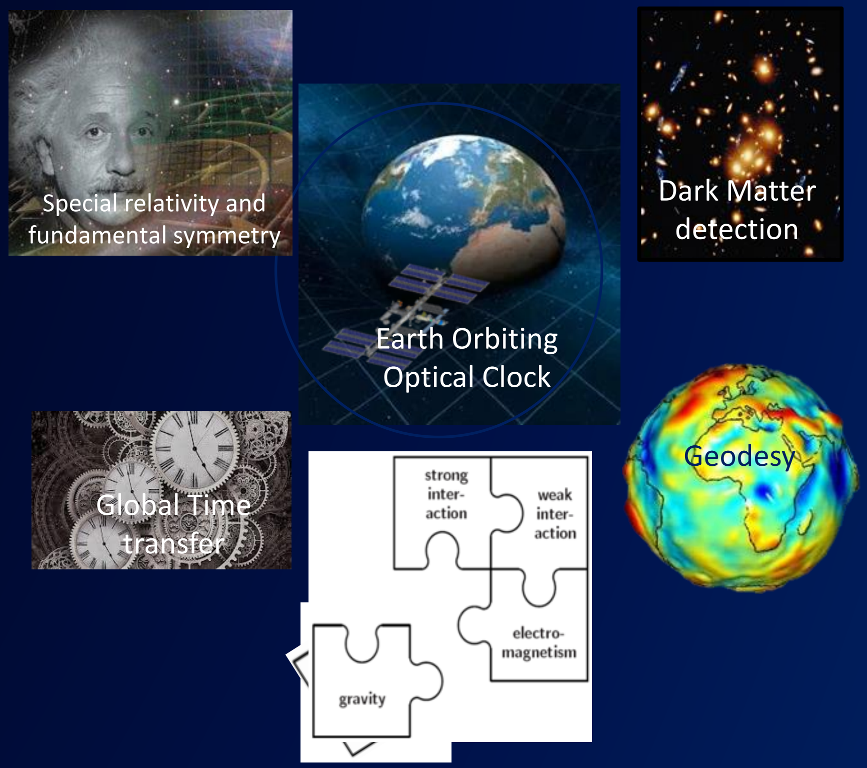
Free Flyer Keystone Mission Candidate - FOCOS
Fundamental physics with Optical Clock Orbiting in Space

Objective
- Perform high-resolution tests of fundamental physics with 10^{-18} accuracy optical clocks in space
  - Red-shift and local position Invariance of general relativity by ~ 3 orders of magnitude
  - Search for time variations in the fine structure constant.
  - Search for ultra-light (<1eV) dark matter candidate particles.
- Enable geodesy to mm precision & demonstrate global time transfer to 10^{-18}

Heritage
- 2004: PDR for NASA's Primary Atomic Reference Clock in Space (PARCS); Neil Ashby, NIST
- 2006: Study Complete for Rubidium Atomic Clock Experiment (RACE); Kurt Gibble, Penn State
- 2010 & 2014 ESA Cosmic Vision M4 proposals (SAGAS & STE-QUEST)
- 2017: Completion of 2 NRA investigations to support ESA's Space Optical Clock Study (NIST)
- 2019: SDT team selected by NASA to evaluate objectives for Optical Clock in Space.
- 4 NRA investigators participating in ESA's 2021 Atomic Clock Experiment in Space (ACES)

Relevance/Impact
- 2011 Decadal FP2: Understand the fundamental forces and symmetries of nature
- 2003 Q2C NRC Report & 2017 FPSRB White Paper
- A violation of Einstein's theories at any level will require a re-write of physics.
- Discovery of dark matter particle or reduction of possible candidates is ground-breaking
- Pathfinder for Global clock network for science and exploration

Approach
- Use science definition team to finalize science objectives, requirements, and concept.
- Perform technology maturation of critical elements, including time/frequency link
- Select investigators through ROSES NRA.
- Partner with NIST and engage potential international partners with goal to cost share.



ISS/DSG Keystone Mission Candidate - QTEST

Quantum Test of Equivalence and Space Time

Objective

- Use atom interferometry to probe with a factor of 10^{+4} higher resolution than currently if Einstein's Equivalence Principle holds for quantum test particles. (more than x10 better than MicroSCOPE)
- Improve testing of the standard model of particle physics by x10 (fine structure constant).
- Search for ultra-light dark matter candidates with improved precision.

Heritage

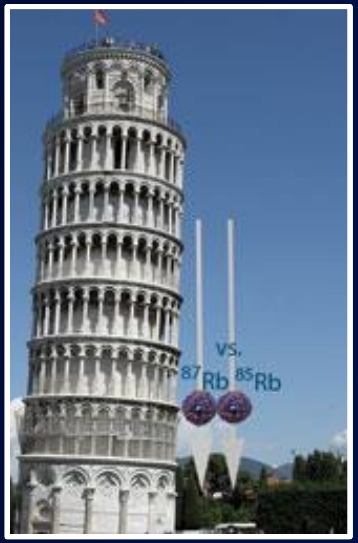
- 2006: Completed 5-year flight study "Quantum Interferometer Experiment (QuItE) " (Kasevich, Stanford).
- 2014: ESA M4 STE-QUEST Mission proposal
- 2017: Completed study of ESA's Quantum Weak Equivalence Principle (QWEP). (Mueller, Stanford)
- 2017: Completion of Quantum test of Equivalence (QTEST) Mission study, with JPL Team X evaluation.
- 2020: CAL demonstrates atom interferometry in space

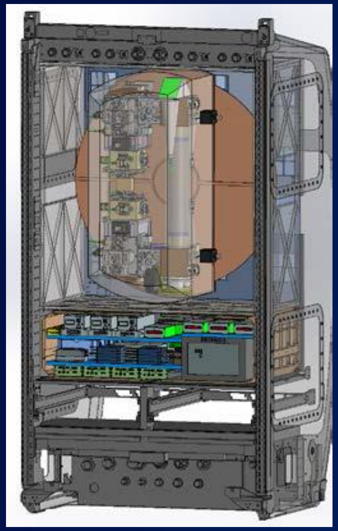
Relevance/Impact

- 2011 Decadal FP2: Understand the fundamental forces and symmetries of nature
- 2003 Q2C NRC Report & 2017 FPSRB White Paper
- A violation of Equivalence Principle at any level will require rewriting physics textbooks.
- Discovery of dark matter particle or reduction of possible candidates is ground-breaking
- Extend the EEP test to particle wave packets and wave function under gravity.

Approach

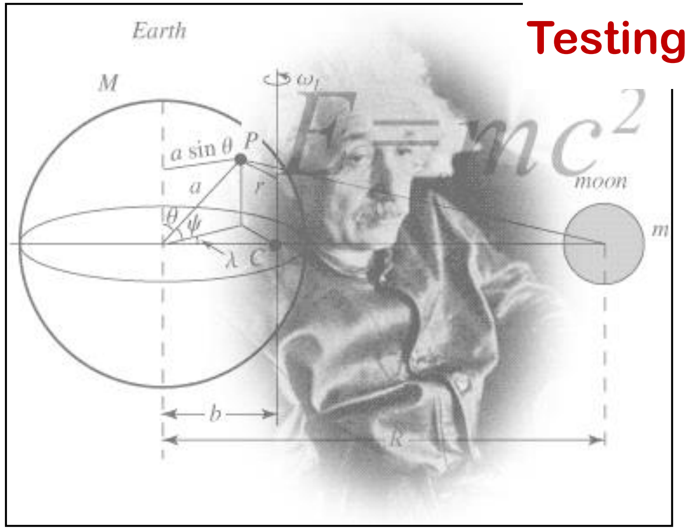
- Use high-flux Rb85 and Rb87 ultra-cold atom sources as test masses
- Gravity direction modulation
- Perform technology maturation of critical elements to TRL 5-6 by end of FY24 (PDR)
- Select flight investigators through ROSES NRA
- Seek international collaboration with ESA, DLR and CNES (MicroSCOPE)





ISS QTEST payload

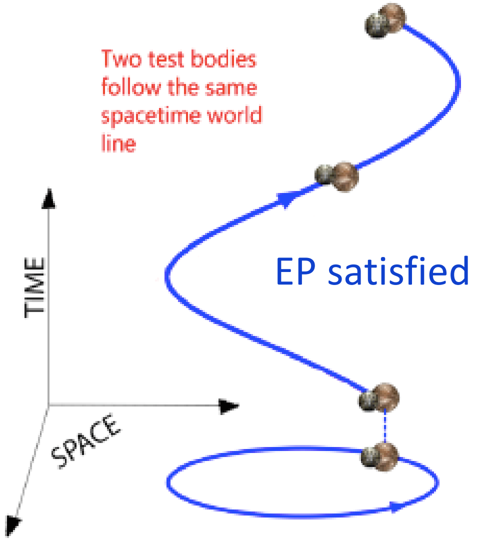
Testing General Relativity with Lunar Laser Ranging (LLR)

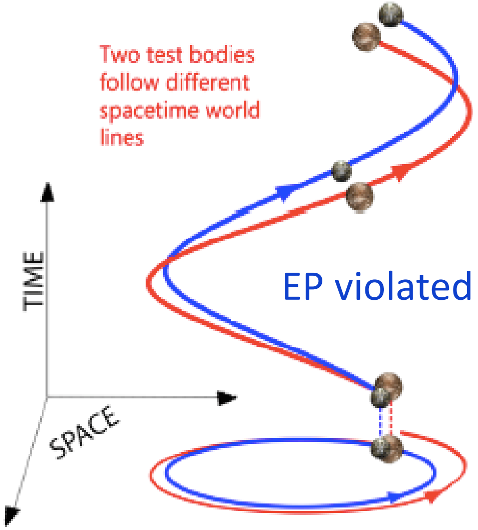


Testing for Violation of the Equivalence Principle (EP) in lunar orbit:

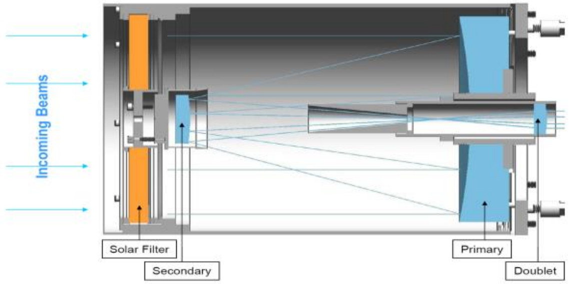
Legacy of the Apollo: LLR is posed for breakthrough science

Science	Current (1 cm)	1 mm	0.1 mm
Weak EP	$\vert\Delta a/a\vert<2.4\times10^{-14}$	$<10^{-14}$	10^{-15}
Strong EP	$\vert\eta\vert<3.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
PPN parameter β	$\vert\beta-1\vert<7.2\times10^{-5}$	$<10^{-5}$	10^{-6}
Time variation of G	9.5×10^{-15} yr^{-1}	5×10^{-15}	$<1\times10^{-15}$
Inverse Square Law	$\vert\alpha\vert<3\times10^{-12}$	10^{-12}	10^{-13}

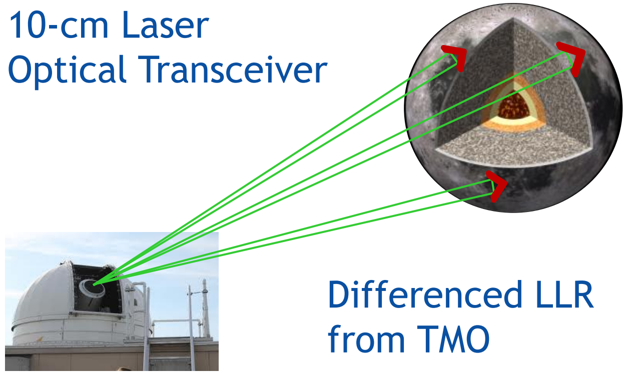




- **Differenced Lunar Laser Ranging (DLLR):**
  - Active Laser Optical Transceiver (<1W, 10-cm aperture) on a CLPS lander achieve orders of magnitude improvement in SNR significantly improving lunar ranging precision.
  - Advanced LLR from TMO: 1-m telescope with a high-power (2kW average) CW laser to range the moon
  - It is expected to achieve ~30 um range precision, rejecting the most common mode Earth atmospheric perturbation.
- **New science investigations of the moon:**
  - Improved tests of relativistic gravitation.
  - Enhances knowledge of deep lunar interior, beyond GRAIL;
  - Lunar core: shape, rotation, dissipation, free libration.



10-cm Laser Optical Transceiver



Differenced LLR from TMO